Запропонований алгоритм автоматичної синхронізації роботи обігрівачів за умови обмеженого енергоресурсу. Особливістю алгоритму є автоматичний розподіл обігрівачів на пріоритетні та непріоритетні за умови передбачуваності роботи обігрівача. Пріоритетні обігрівачі синхронізують свою роботу у часі таким чином, щоб залишковий електричний ресурс використовувався максимально повно та був доступним кожному непріоритетному обігрівачеві. Алгоритм може бути використаний для вдосконалення системи управління електричним опаленням згідно концепції «розумного будинку»

Ключові слова: електричне опалення, обігрівач з термостатом, розподіл потужності, автоматичне управління енергоспоживанням

Предложен алгоритм автоматической синхронизации работы обогревателей при условии ограниченного энергоресурса. Особенностью алгоритма является автоматическое деление обогревателей на приоритетные и неприоритетные из условия предсказуемости работы обогревателя. Приоритетные обогреватели синхронизируют свою работу во времени таким образом, чтобы остаточный электрический ресурс использовался максимально полно и был доступным каждому неприоритетному обогревателю. Алгоритм может быть использован для совершенствования системы управления электрическим отоплением согласно концепции «умного дома»

Ключевые слова: электрическое отопление, обогреватель с термостатом, распределение мощности, автоматическое управление энергопотреблением

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DEVELOPMENT OF THE ALGORITHM FOR THE AUTOMATED SYNCHRONIZATION OF ENERGY CONSUMPTION BY ELECTRIC HEATERS UNDER CONDITION OF LIMITED ENERGY RESOURCE

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1. Introduction

Using the technology of intelligent networks for energy supply management based on collection and real-time processing of information about the generation and consumption of electric energy has long been a norm in Europe and the United states. But the rules for the creation of smart power networks are focused on solving the task of improving the efficiency of electric energy supply mostly to large consumers. Development of the technology of «smart home» initiated consideration of the concept of creating smart energy grids in relation to the individual as a consumer of electricity. This implies control over power supply within a single private house or apartment when an average person is equipped with a tool for planning and managing the consumption of electricity consumption at his/her sole discretion.

One of strategically important issues of energy security of Ukraine and the countries of Europe today is to reduce the consumption of natural gas. This task is particularly relevant in winter, when a significant amount of natural gas is consumed for heating premises. Therefore, one can predict that in the nearest future, in Ukraine and European countries, premises will be heated more frequently by electrical energy.

A massive transition to electric heating of premises under conditions of the implementation of national objective in Ukraine and the countries of Europe related to a significant reduction in energy consumption necessitates to rethink the process of control over electric heating of premises. It is required that the algorithms that control power supply to premises should include mechanisms for planning the amount of electric energy consumed by an individual. This is especially true of such energy-intensive processes like heating the premises.

Therefore, it is an important task for Ukraine and the countries of Europe to work out an approach for creating systems to control electric heating of premises in a house or apartment that would take into consideration not only information about the desired temperature regime, but also information on the desired amount of electricity needed for heating.

2. Literature review and problem statement

Initially, the concept of Smart Grid was applied in relation to large consumers of electricity [1]. For example, authors in paper [2] considered an algorithm for the distributed control over electric energy demand, based on a game theory, in order to reduce a peak demand of a group of residential users. The user is a group of devices and thus the task on the allocation of electricity is resolved not among devices, but rather among groups of appliances, that is, among apartments or houses.

Given wide application of information technologies in buildings, it has become possible to use the ideas of the Smart Grid concept at the level of separate houses or apartments.

The task on planning and managing the allocation of electric energy between devices in a building or apartment with the participation of an individual in order to achieve more economical electricity consumption is solved within the framework of the concept of «smart home». According to this concept, a separate class of systems was developed that control energy consumption in a house, Smart Home Energy Management (SHEM). Paper [3] states that the search for effective approaches to the management of power consumption in SHEM systems has remained a topical issue because the solutions already proposed cannot provide for minimal power consumption under conditions of comfortable temperatures at premises.

According to the classic approach, creating climate-control systems employ the principle of temperature control based on a deviation in the actual temperature at premises from the desired temperature. In this case, the task is solved on the optimal tuning of PI or PID controller based on the integrated criteria of performance efficiency of control system [4]. This approach, however, is not applicable for the coordinated control over distributed objects with properties that constantly change over time.

Paper [5] describes a solution when the power consumption control algorithm includes a mathematical model that characterizes the physical process of heating premises in order to predict the time when each heater is to be connected to a power grid. In this case, however, the authors fail to consider a possibility to assign the limit for a user based on total power, nor did they investigate the process of electricity allocation under conditions of a limited energy resource.

The most global and promising approach to solving the task on efficient management of energy consumption in a building is described in paper [6]. According to this approach, power consumption is managed in line with a certain scenario that is generated by the intelligent house management system. Making up a scenario implies taking into consideration a lot of input data that describe the type of house, main reasons of electricity consumption, behavior of house residents, etc. The disadvantage of a given approach is its large cost and complexity of the system in general.

Paper [7] presented an algorithm for managing power consumption by electric heaters based on the theory of collective behavior. The considered algorithm, however, does not rule out a situation when most of the heaters are simultaneously connected to a power grid. Such a situation occurs because of the feature of the algorithm that operates thermostats of relay character, which are turned on at the lower temperature limit and are turned off at the upper temperature limit. This leads to an incomplete use of the allocated energy resource even in the absence of ensuring the assigned thermogram in certain heating zones.

Paper [8] proposed, in order to improve efficiency of power management, to use forecasts for the generated and consumed electricity. For this purpose, the authors suggested a structure of an expert system based on the use of adaptive neural-fuzzy logic unit for forming a conclusion and controlling information. The shortcoming of this solution is that the expert system requires considerable time for information acquisition, and it will not be able to respond quickly to short-term changes in the character of power consumption or heating conditions at premises. Therefore, the issue of periodic and partial use of the energy resource allocated to a user for heating the premises over short time intervals remains to be solved.

Papers [9, 10] identified the most promising directions in the development of technologies Smart Grid and Smart Home. They emphasize that it is a relevant and promising task to improve the efficiency of SHEM systems in order to enable the owner of a house to control, manage and store energy.

Authors of paper [11] received a non-trivial result. Contrary to the intuitive understanding that the largest energy with a limited power comes to heating zones at a simultaneous connection of all existing electrical heating devices, it turned out that the individual connection of only part of the heaters in line with a procedure of mass service, whose total capacity is equivalent to the limit of heating capacity, makes it possible to obtain a greater effect.

Authors in [7] considered such a model of collective behavior of automated machines that control the process of allocating limited electrical power in a heating network that implies that each machine makes its decision regardless of a particular state of other machines. Self-organization of the network is executed under the influence of collective modes: average «price» of electrical power, total current capacity of a thermal field, boundary current capacity, which can be utilized by the sources of heat. These magnitudes serve as synergetic parameters of order in the process of self-organization of a heating network. Each automated machine takes decisions regarding the state of a heat source under its control, considering the specified parameters of order and the state of its «own» heat source. In paper [12], such a collective of automated machines was named «automated gas». The analogy here implies that the behavior of a separate gas molecule is predetermined by such thermodynamic parameters as pressure, temperature, volume, regardless of the state and configuration of other molecules. The thermodynamic parameters themselves are predetermined by the interaction and constraints of all molecules of gas. Such an approach minimizes the amount of information that is required to a local automaton for making a decision. This, in turn, greatly simplifies the task of decentralized network-centralized control over heat allocation. The shortcoming of the considered approach is the possibility of non-optimal power allocation in a network with the finite number of controlled heat sources. As shown in [13], the algorithm of collective power allocation is closer to the optimum the larger the number of controlled heat sources in a network. The non-optimality here manifests itself in the fact that the rest of the non-allocated power might be larger than that which is achieved by sorting out all possible states of the system. However, given a large number of heat sources in a thermal field, full sorting complicates the system. Over the period of its execution, the situation in the power system of a thermal field power may change and thus the solutions obtained by full sorting may prove to be not only irrelevant but even opposite to those expected.

The excess power that was not allocated could be reduced almost to the optimal level by joint action of automated machines combined in coalition groupings. Papers [12] and [14] demonstrate the possibility and effectiveness of coalition organization of the collective of automata in systems of mass servicing.

Thus, we can conclude that there is no approach to manage energy consumption in a house when electrical appliances «talk» to each other under conditions of limited energy resource, controlled by the user. Therefore, there are grounds for the creation of algorithm for the automated synchronization of operation of electric heaters considering the features of thermostats functioning, and for studying patterns of capacity allocation based on the proposed algorithm.

3. The aim and objectives of the study

The aim of present study is to create a new approach to managing direct electric heating, according to which the allocation of energy, close to the optimal, is performed by creating coalition groups of heat sources. This would enable the maximal utilization of the energy resource allocated for electric heating of premises.

To accomplish the aim, the following tasks have been set:

– to construct an algorithm for the allocation of power among electrical heaters that would enable operation synchronization in time with the aim of maximizing the use of the allocated power limit;

– to establish patterns in the allocation of power among electrical heaters for different situations when heating the premises.

4. Algorithm for the automated synchronization of work of heaters and method for studying the allocation of power

Given the fact that the rise in gas prices is significantly ahead of the line of increasing electrical tariffs, experts now predict a higher demand for electrical heating systems, which apparently will cost much cheaper than centralized heating and even a gas heating boiler.

For heating an area of 10 m^2, in a properly thermally insulated premise, with ceilings no higher than 3 m, 1 kW of power is required. Thus, heating a 3-room apartment with an area of 60 m^2 would require a power of about 6 kW. However, the electricity grids in most high-rise buildings will simply not sustain such a load if the electricity is demanded by all consumers simultaneously. Thus, a significant limiting factor in the implementation of electric heating is the power limit in a network of power supply to a heating object at the level, which can generally be much lower than the total installed power of heaters, required to maintain a comfortable temperature distribution (Fig. 1).

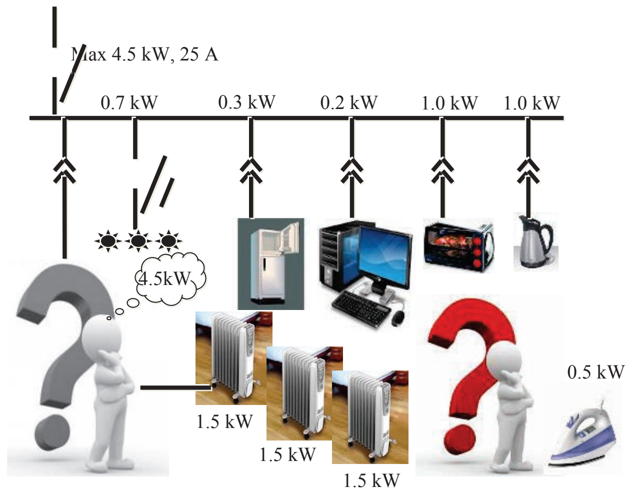

Fig. 1. Illustration of the task on the direct connection of electric heating to the electricity grid of an apartment

Exceeding the power limit can be avoided by synchronizing the work of heating devices with other electric consumers so that the reallocation of power is enabled automatically. The possibility of such regulation is predetermined, on the one hand, by the inertia of electrical heating devices, and, on the other hand, by the intermittent operating mode of household electrical devices (refrigerator, iron set, washing machine, etc.).

A given problem can be solved by ordering the states of heating devices in time. The process of direct electric heating needs to be managed. This means that at any point in time the total power of plugged heating devices shall not exceed the level of permissible capacity, which varies randomly due to connecting/disconnecting various electrical appliances. An example of the synchronization of work of two electric heaters that are turned on and off by their own thermostats when reaching the set temperatures is shown in Fig. 2.

The diagrams show that in the absence of mutual synchronization the maximum power that is spent on heating would reach 3 kW, whereas in the case of synchronization it is only 1.5 kW. Exceeding the permissible power level can be avoided if the work of heating devices is synchronized not only with one but also with other energy consumers so that electric energy is automatically reallocated.

Control system for direct electric heating includes a certain set of electrical heating devices, which are in different zones of the heated facility and is connected to a common source of energy through specialized automated devices – automated machines. The latter, by sharing information in real time, form in the space of a heating facility the subsystem of local heat sources whose total capacity does not exceed the power limit allocated for heating, which randomly varies over time. The composition of this subsystem changes in real time in order to maintain the preset temperature distribution in heated zones under condition of meeting the limitation for its total capacity.

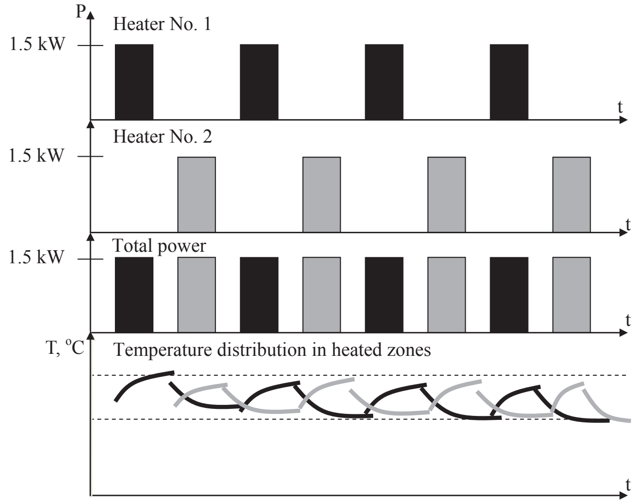

Fig. 2. Limiting the power of direct electric heating through the synchronization of switching on/off the heating devices: $P1$, $P2$ – rated power of heaters, $P\Sigma$ – total power of the system of electric heating, T – heat source temperature, °C

Automated machines control power supply to electric heating devices, which are subsequently turned on by their own thermostats except when there is a threat of exceeding the power limit. In these cases, the machines disable heating devices without waiting until their own thermostats are triggered.

4. 1. Algorithm of the allocation of power among electrical heaters that enables the synchronization of work in time

The algorithm to control heaters that enables the synchronization of their work in time was created for the conditions of centralized control and the absence of information about temperature mode in the heating zones. The implication is that the temperature mode in heating zones is set by the user who manually sets a thermostat for each heater.

Initial data for the algorithm are the following information:

– number of the heater;

– state of the heater (active or passive, that is if the thermostat's contacts are closed or open);

– capacity of the heater, kW;

– total power of electric appliances that are connected to the electric grid and which are not heaters ($P_{not\text{-}heater}$);

– the limit set by the user for the total power of all electric appliances connected to the electrical grid (P_{limit}):

$$\sum_{i=1}^{N_{heaters}} P_{heater.i} + P_{not\text{-}heater} \le P_{\lim it},$$

where $P_{heater.i}$ is the power of the i-th heater, kW; $N_{heaters}$ is the number of heaters, connected to the grid.

The criterion of maximal utilization of the allocated energy resource by electric heaters over a certain time t, taking into account the limit, specified by the user, for a total power P_{limit}, is described by the system of equations:

$$\begin{cases} \int_0^t [P_{limit} - (P_{not\text{-}heater} + \sum_{i=1}^{N_{heaters}} P_{heater.i})]dt \to 0; \\ \sum_{i=1}^{N_{heaters}} P_{heater.i} + P_{not\text{-}heater} \le P_{limit}. \end{cases} \quad (1)$$

The task on achieving the maximum use of the allocated energy resource is complicated by the fact that in formula (1) all terms in the system of equations are the magnitudes that change over time in a random fashion. This is due to the unexpected operational modes of electrical appliances that are not heaters, and due to unpredictable changes in heating conditions. Following each change of at least one term in the system of equations (1), it is necessary to conduct multiparametric optimization based on temporal shifts in the moments of turning on the heaters. This is a rather time-consuming task whose complexity level increases exponentially with an increase in the number of heaters. Under conditions of limited time for decision-making and limited computational resources of the system, a significant complication of the algorithm that allocates energy resource among heaters is inacceptable. Moreover, solving the problem of multiparametric optimization with an increase in parameters does not warrant the achievement of a global optimum.

Therefore, we propose a heuristic algorithm of energy resource allocation among heaters, which is based on the time-dependent synchronization of turning a selected part of the heaters with a predictable mode of operation that remains constant over a long time. Synchronizing the turning on of a selected part of the heaters in time makes it possible to allocate energy resource among another part of heaters so that this achieves the maximal utilization of the allocated energy resource.

The main part of the heuristic algorithm for the allocation of energy resource among heaters with the synchronization of work in time is shown in Fig. 3. The algorithm starts with the procedure of forming «coalition groups of heaters» according to their power, which is executed in the subprogram with the respective name (block 2 in Fig. 3). In accordance with this procedure, the allocated total energy resource is conditionally divided into parts whose size corresponds to the power of active heaters that are connected to the grid. The allocation of the total energy resource into parts is based on the criterion of maximizing the use of a given resource in accordance with formula (1)The allocation of the total energy resource into parts makes it possible to separately and individually control the allocation of each part of the energy resource. For this purpose, we shall introduce a conditional notion «a group of users», which is assigned the right to allocate a certain part of the total energy resource.

For example, four heaters with a power of 0.8, 1, 1.5, and 2 kW are connected to the grid. The heaters at the current time moment are given 3 kW. According to formula (1), the total energy supply of 3 kW is divided into two parts – 1 and 2 kW, respectively. Thus, we have two «groups»: the first «group» allocates among the heaters a part of the resource of 2 kW, and the second – 1 kW.

A decision on the allocation of appropriate part of the total energy resource to a «group» or another heater is taken as a result of execution of routines in blocks 3–5 in Fig. 3. A feature of the algorithm for the allocation of part of the total energy resource within a «group» is in the fact that one of the heaters is assigned a status by the «group» that allows this heater to always receive the energy resource, in contrast to other heaters. Two conditions must be met to assign such a status:

1. Power of the heater must be equal to the power of the «group», that is, to the size of part of the total energy resource, which is given to the «group».

2. The heater should operate under a mode of maintaining the temperature in the heated area, that is, there should be

observed a cyclical character of turning on and off the heater by its thermostat.

In fact, the «group» constantly allocates its energy resource to the heater with a special prioritized status («own» heater), and when it shuts off, it offers free energy resource to other heaters. This means that prioritized is given to the heaters whose power is sufficient to maintain a user-defined temperature mode in the heated zone.

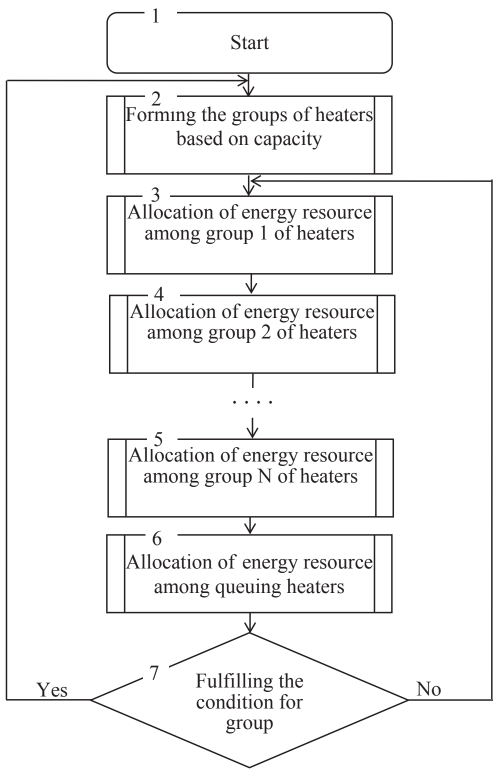

Fig. 3. Block diagram of main part of the heuristic algorithm for the allocation of energy resource among heaters with the synchronization of their work in time

To enable the work of «own» heaters from all «groups» with the same time period, the periods of almost all «own» heaters (except for the one that sets a total maximum period) are artificially prolonged by a time offset of the moment of connection to the electric network. That is, over a certain time, the «group» declines the «own» heater's request for energy resource (contacts of the thermostat are closed). In this case, the period of heater T_{heater} consists of three components:

$$T_{heater} = T_{switched\text{-}off.passive} + T_{switched\text{-}off.active} + T_{switched\text{-}on},$$

where $T_{switched\text{-}off.passive}$ is the time during which the heater is switched off and is in a passive state, min; $T_{switched\text{-}off.active}$ is the time during which the heater is switched off and is in an active state, min; $T_{switched\text{-}on}$ is the time during which the heater is turned on, min.

In addition to the same period, the synchronization of heaters work in time implies a certain phase shift in the schedule of operation of each appliance relative to the start of the period. This phase shift is defined by the following rules of synchronization of work of «own» heaters in «groups»:

1. The allocation of free resource over time. This rule is always applied to synchronize the work of powerful heaters so that the corresponding «groups» can offer, permanently in time, the total free resource to other heaters of the same power or to less powerful heaters. If such a synchronization is neglected, then in certain moments, when both «own» and powerful heaters are off, there may occur an incomplete use of the allocated energy resource when it is constantly needed by a third-party heater.

This rule can also be used to synchronize the work of less powerful «own» heaters if the number of less powerful third-party heaters exceeds the number of more powerful heaters.

If the first rule of synchronization of «own» heaters is applied, the moment of turning on the heater from the current «group» must coincide with a moment of turning off a heater from another «group» with which it is synchronized, – this is a condition for synchronization.

2. Consolidation of free resource in time. This rule always applies to synchronize the work of less powerful heaters so that the respective «groups» can offer consolidated free resource to more powerful third-party heaters when both «own» heaters are off. Such a synchronization of work of less powerful heaters in «groups» is performed when the number of more powerful third-party heaters exceeds the number of less powerful heaters.

If the second rule of synchronization of the work of «own» heaters is applied, the moment of turning on the heater from the current «group» must coincide with a moment of turning on the heater from another «group» with which it is synchronized, this is a condition for synchronization.

Under condition of conducting a procedure of synchronization of the heater from the current «group», the necessary phase shift in the schedule of the heater relative to the start of the period is assigned by increasing parameter $T_{switched\text{-}off.active}$. However, if there is a too long period between the moment the heater enters active state and the moment it is turned on it according to the condition of synchronization, the inequality holds:

$$T_{switched\text{-}off.passive} + T_{switched\text{-}off.active} + T_{switched\text{-}on} > T_{period},$$

which is unacceptable. In addition, increasing parameter $T_{switched\text{-}off.active}$. leads to a decrease in the mean surface temperature of the heater and, accordingly, the deterioration in the accuracy of maintaining the set temperature in the heated area. Therefore, under condition a heater enters the «group» for the first time, its state is defined by the heater with which it synchronizes its work.

Next, free energy resource of all «groups» is consolidated and offered to all other third-party heaters without a special status, which form the so-called «queue.» The free consolidated energy resource from «groups» is given to the heater from a «queue» for which the condition of maximum utilization of the allocated total energy resource is met. If the condition of maximum utilization of the allocated total energy resource holds for several heaters in the «queue», the decision shall be made based on a comparison of the calculated priorities of the i-th heaters according to formula:

$$\Pr_i = 1 - \frac{T_{switched\text{-}on.i}}{T_{switched\text{-}on.i} + T_{switched\text{-}off.active.V}}.$$

To prevent frequent turning on/off heaters from the «queue», upon turning, the heater is guaranteed to receive energy resource over the period that is defined by the user, regardless of its prioritized.

Thus, the result of execution of a subroutine in block 6 in Fig. 3 is the decision on the allocation of energy resource to heaters from the «queue».

In block 7 in Fig. 3 we check fulfillment of the following conditions for the redistribution of «groups»:

1. There are «groups» without «own» heater over a long time (3 periods).

2. One «group» has more than two heaters with similar power waiting in the «queue».

3. A change in the limit set by the user for total power P_{limit}.

4. A change in the total power of electrical appliances connected to the grid, which are not heaters $P_{not\text{-}heater}$.

If at least one of the conditions for the redistribution of «groups» is met, there is a transition to block 2 to form a new combination of «groups». If none of the conditions for the redistribution of «groups» is met, there is a transition to block 3. After that, routines for the allocation of energy resource in «groups» and «queue» are performed again.

4. 2. Simulation modeling of the process of allocation of power among electrical heaters

To study the process of power allocation under condition of the automated synchronization of work of heaters, we used simulation modeling of the processes of heat exchange between a heater, a room, and external environment.

Computational experiment was conducted for a three-room apartment whose schematic is shown in Fig. 4. In this apartment, according to the plan, one can select four zones for heating – three rooms and a kitchen with corridor. There are one electric heater and an additional heat source (an option is a central heating system battery) in each heated zone. Parameters for the heated zones are defined in the course of field experiments [9] and are given in Table 1.

Processes of heat exchange in each heated zone are described by a mathematical model of the same type that simulates the dynamics of temperatures at the surfaces of the heater and the room and which forms the basis of the procedure for testing heating devices [10]:

$$\begin{cases} \tau_{heater}\cdot\dfrac{dT_{heater}}{dt}=\dfrac{P_{heater}}{\sigma_{heater}}-(T_{heater}-T_{room}); \\ \tau_{room}\cdot\dfrac{dT_{room}}{dt}= \\ =(T_{heater}-T_{room})\cdot\dfrac{\sigma_{heater}}{\sigma_{room}}+\dfrac{P_{additional}}{\sigma_{room}}-(T_{room}-T_{environment}), \end{cases} \quad (2)$$

where $P_{additional}$ is the power of heat flow from additional sources in the room (except for the heater), W; σ_{room} is the coefficient of heat transfer of the room relative to the external environment, W/°C; $T_{environment}$ is the temperature of the environment, degrees; T_{heater} is the surface temperature of the heater, degrees; P_{heater} is the power of the heater, W; T_{room} is the room temperature, degrees; σ_{heater} is the coefficient of heat transfer of the heater, W/°C; τ_{heater} is the time constant of the heater min.; τ_{room} is the time constant of the room, min.

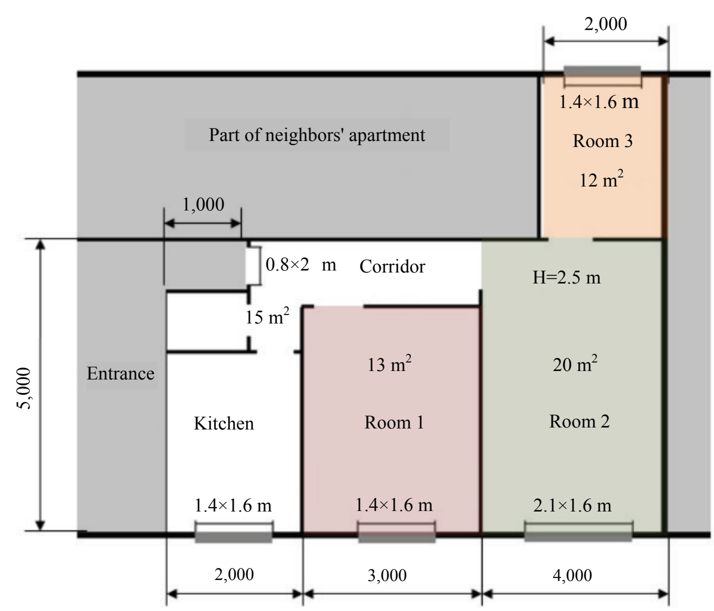

Fig. 4. Layout of the apartment – the modeled object of thermal processes

Table 1

Parameters of the heated zones of apartment

No. of heated zone	Initial temperature of heater surface, °C	Initial temperature at apartment, °C	Room area, m²	Power of heater, W	Power of heat flux from additional source, W	Coefficient of room heat transfer relative to the environment, W/°C	Coefficient of heat transfer of heater, W/°C	Room time constant, min	Heater time constant, min	Ambient temperature, °C
1	20	20	13	1,000	70	15.04	11.1	50	17.3	0
2	20	20	20	1,500	120	22.56	16.7	55	17.3	0
3	20	20	12	1,000	70	13.7	11.1	59	17.3	0
4	20	20	15	1,500	200	18.8	16.7	50	17.3	0

In formula (2), power of the heater P_{heater} is derived from formula:

$$P_{heater} = P_{heater} \cdot k1 \cdot k2,$$

where $k1$ is a factor that sets the state of the heater according to the proposed power allocation algorithm (1 – connection to the grid, 0 – disconnection from the grid); $k2$ is a coefficient, which sets the state of the heater according to the algorithm of the heater thermostat operation:

$$k2 = \begin{cases} 1, & \text{if} \quad T_{heater} > T_{upper}; \\ 0, & \text{if} \quad T_{heater} < T_{lower}; \\ k2, & \text{if} \quad T_{lower} \le T_{heater} \le T_{upper}, \end{cases}$$

where T_{lower} and T_{upper} are, respectively, the lower and upper limits of the range over which a thermostat maintains the surface temperature of the heater, degrees.

5. Results of study of the process of automated synchronization of electric heaters operation

Consider results of the study into operation of control system of heaters for the criterion of maximum synchronization under condition of certain situations when heating the premises.

5. 1. First run of the system that manages energy consumption of heaters

Under condition of the first run of the system that manages energy consumption no heater is part of the group, and surface temperatures are equal to the temperature in the room. Fig. 5 confirms that at the time of start of the system that manages energy consumption of heaters none of the heaters is included in groups prior to minute 30 after the launch of the system (this point is accepted to be the coordinate origin). According to the proposed algorithm for the automated synchronization of heaters operation, in this time interval the allocation of power should proceed evenly with alternate turning on/off the heaters and without exceeding the limit for power.

This is confirmed by Fig. 6.

It shows that the heaters with a capacity of 1 kW were alternately turned on/off with a period of 4 minutes after the launch of the system and up to minute 30 (Fig. 6).

After 11 minutes, the limit for power increases to 2,500 W (Fig. 5, *a*) and there is a resource for heaters with a capacity of 1,500 W. Thus, starting at this moment, heaters with a capacity of 1.5 kW must be similarly turned on. This is confirmed by Fig. 7. It shows that heaters with a power of 1.5 kW were alternately enabled and disabled with a period of 4 minutes from minute 11 to minute 30.

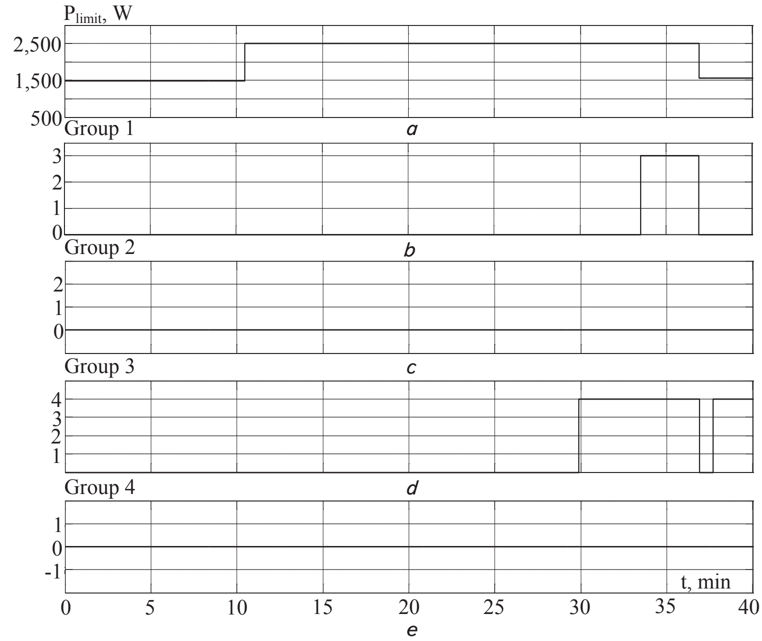

Fig. 5. Change over time:
a – the limit of power for the electric heating of apartment; *b* – number of «own» heater from the first «group»; *c* – number of «own» heater from the second «group»; *d* – number of «own» heater from the third «group»; *e* – number of «own» heater from the fourth «group»

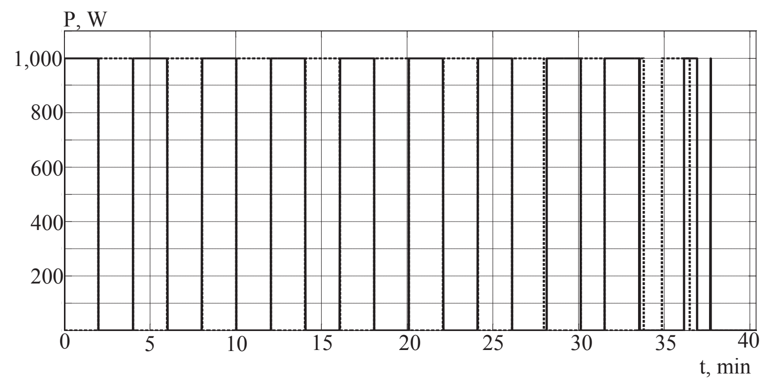

Fig. 6. Change in the power used by the first (dotted line) and third (solid line) heaters over time

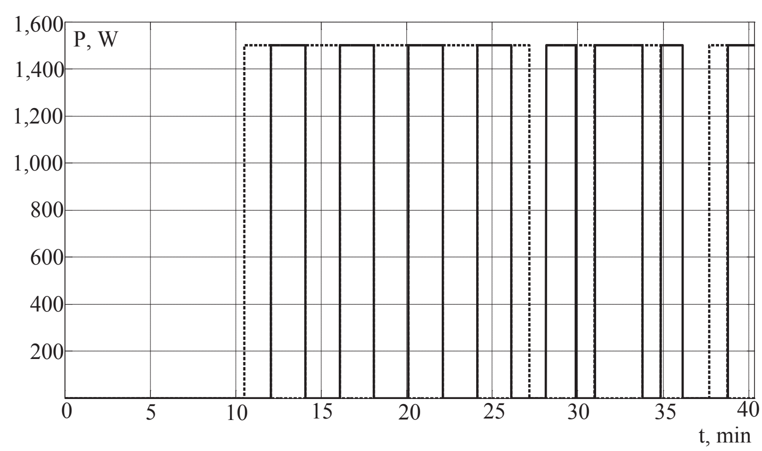

Fig. 7. Change in the power used by the second (dotted line) and the fourth (solid line) heaters over time

Thus, the results of computational experiments in Fig. 6 and Fig. 7 confirm correct work of the algorithm that automatically synchronizes heaters for the situation when no heater is included in the groups.

5. 2. Work of the system that manages power consumption of heaters under condition of synchronization of the operation of heaters with the same capacity

To study the process of allocation of power under condition of synchronization of the operation of heaters with the same capacity, we chose a time interval when the power limit is between 2,000 and 2,500 W (Fig. 8, *a*). In this case, the prioritized heaters that are included in groups are the heaters with a capacity of 1000 W (Fig. 8, *b*). In Fig. 8 this time interval is marked with a gray shading.

Fig. 8 shows that between minutes 356 and 371 over the course of experiment, we observed the work of heaters control system with the synchronization in time of the operation of heaters with a capacity of 1 kW. Fig. 8, *b*, *c* shows, in the region of the chart highlighted with a shading, that during this time interval the heaters are included in the first and second groups, which control the allocation of power of 1 kW.

The reason why the heaters with a capacity of 1 kW are included in the first and second groups is that over an interval from minute 356 to minute 371 there is limit for a power of 2,470 W caused by turning on a household appliance (Fig. 8, *a*). For this value of power limit, the optimum combination of heaters under condition of the maximum utilization of the allocated resource is the combination of two heaters with a capacity of 1 kW each.

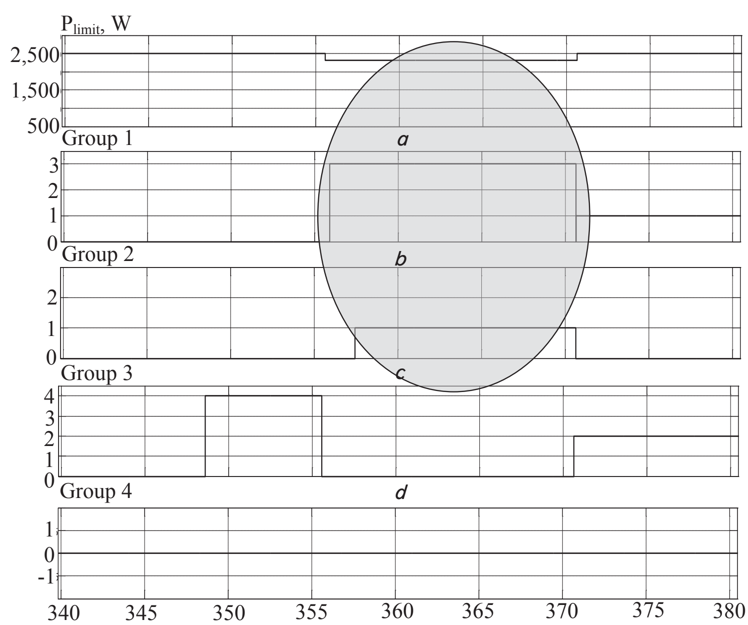

Fig. 8. Change over time: *a* — the limit of power for the electric heating of apartment; *b* — number of «own» heater from the first «group»; *c* — number of «own» heater from the second «group»; *d* — number of «own» heater from the third «group»; *e* — number of «own» heater from the fourth «group»

Thus, over this interval, according to the proposed algorithm, there must occur the synchronization in time of work of the first and third heaters with a capacity of 1 kW in line with the rule of consolidation of resource consumption. That is, they must be turned on simultaneously. Fig. 9 confirms this statement. Fig. 9 shows that starting at minute 358 the first and third heaters are turned on simultaneously. That is, the synchronization of work of the first and third heaters ends at minute 358, and the synchronization of the process of work of heaters in time lasted 2 minutes. This ensures the maximum length of time interval when the first and third heaters are turned off. Over this interval, the resource of 2,470 W can be used by one of the heaters with a capacity of 1,500 W.

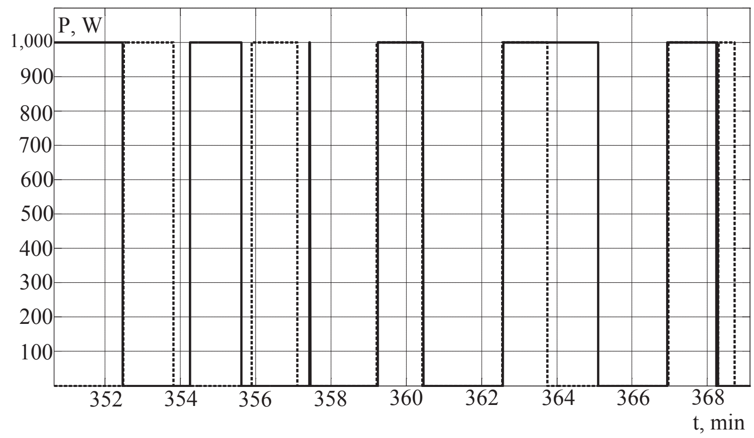

Fig. 9. Change in the power used by the first (solid line) and third (dotted line) heaters over time

Thus, the result of computational experiments in Fig. 9 confirms correct work of the algorithm that automatically synchronizes heaters for the situations when there is a synchronization of heaters with the same capacity.

5. 3. Work of the system that manages power consumption of heaters under condition of synchronization of the operation of heaters with different capacity

To study the process of allocation of power under condition of synchronization of the operation of heaters with different capacity, we chose a time interval when the limit for power is at the level of 2,500 W (Fig. 10, *a*). In this case, the prioritized heaters that are included in groups are the heaters with a capacity of 1,000 and 1,500 W (Fig. 10, *b*, *d*). In Fig. 10, this time interval is marked with a gray shading.

The system that manages heaters at synchronization in time of work of heaters of different capacity operated between minutes 142 and 218 in the course of experiment, when the limit of power for heating was at the level of 2,500 W (the region in Fig. 10 highlighted with a shading).

For a given power limit, the optimal combination of heaters in terms of the maximal utilization of the allocated energy resource is one heater with a capacity of 1,000 W and one heater with a capacity of 1,500 W. Thus, Fig. 10, *b*, *d* shows that over this interval, first, the second heater with a capacity of 1,500 W entered the third group, and then the third heater with a capacity of 1,000 W entered the first group.

According to the proposed algorithm, over this interval, there must occur the synchronization of operation of the second and third heaters with a capacity of, respectively, 1.5 kW and 1 kW in line with the rule of allocation of resource consumption. That is, turning off the third heater should lead to enabling the second heater because the third heater with a greater period of work over this interval was the main heater. Thus, over time, we constantly observed a free resource of power at the level of 1 kW when the third heater did not operate, and at the level of 1.5 kW when the second heater did not work. Fig. 11 confirms this statement.

We investigated separately a change in the power used by heaters that are not included in groups, that is, which are in the «queue». Fig. 12 shows sampling of this power between minutes 270 and 300 of the experiment. Fig. 12 shows that when a free resource is available, the fourth heater with a capacity of 1,500 W is turned on most often as long as there is a free resource or it is not turned off by itself. This is due to the fact that it is the turning on of this heater that ensures maximum utilization of the allocated power resource. Fig. 12 also shows that heaters with a capacity of 1 kW divide the free resource in turn, using it for 1 min each.

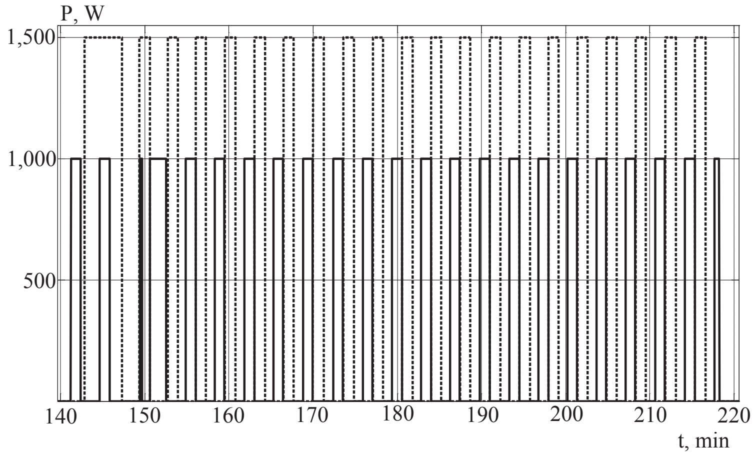

Fig. 11. Change in the power used by the second (dotted line) and third (solid line) heaters over time

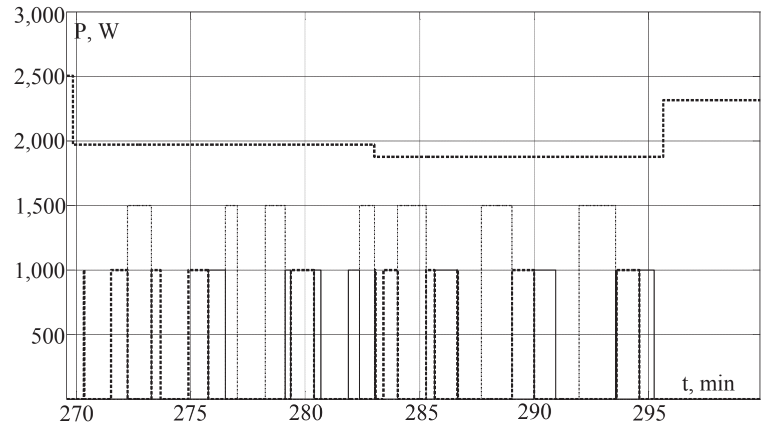

Fig. 12. Change in the power used by the first (solid line), third (dashed line), and fourth (stroke-dotted line) heaters over time

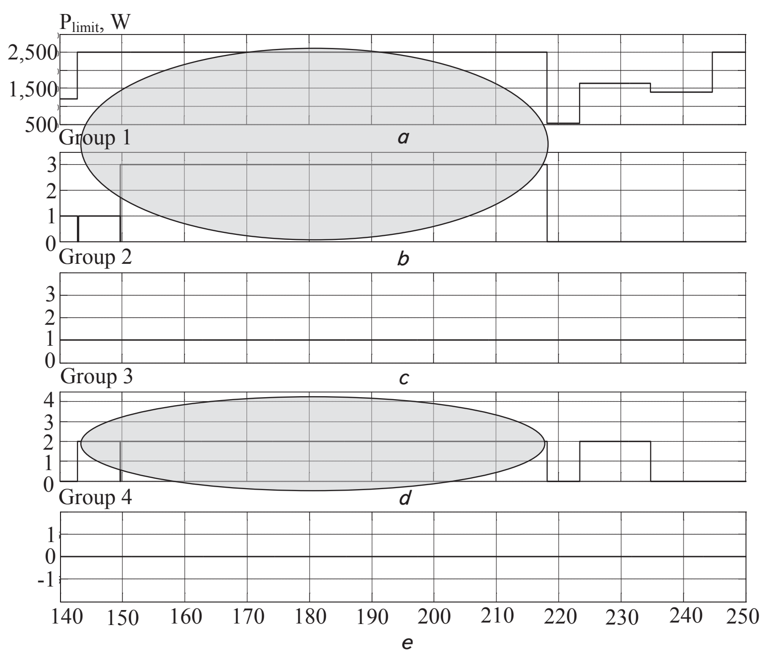

Fig. 10. Change over time: *a* – the limit of power for the electric heating of apartment; *b* – number of «own» heater from the first «group»; *c* – number of «own» heater from the second «group»; *d* – number of «own» heater from the third «group»; *e* – number of «own» heater from the fourth «group»

Fig. 12 shows that non-prioritized heaters from the «queue» receive energy resource over most of the time intervals. This confirms the effectiveness of the synchronization of operation of prioritized heaters in «groups» when a coordinated work of prioritized heaters ensures the allocation of maximum amount of energy resource to the non-prioritized heaters.

5. 4. Work of the system that manages power consumption of heaters over a long time

To study patterns in the allocation of power according to the proposed algorithm that automatically synchronizes heaters under condition of different situations, we took a time interval of 24 hours. In this case, depending on the time of day, we set a different random character of connecting other household appliances to electrical network. In morning and evening hours the frequency of connections of other household appliances was 2–3 times higher.

Analysis of Fig. 13 allows us to draw a conclusion about the absence of exceeding the power limit of 2.5 kW, allocated for the electric heating of an apartment. Short periods when the power limit for heating is exceeded last for 0.01 min and are related to the fact that the system reacts on the event of exceeding the limit. When such an event occurs, the system switches the heaters with a delay equal to the period needed to call the functions in software (in our case, this is a simulation step equal to 0.01 min or 0.6 s).

Fig. 14 allows us to analyze, based on the results of experiment, the work of groups of heaters – we can track the way the heaters, depending on different situations when heating an apartment, entered each group. Fig. 14 shows that under condition of the power limit for heating the apartment at 2.5 kW, heaters most often entered the first and third groups that allocate the resource, respectively, of 1 and 1.5 kW. This is due to the maximum utilization of the established power limit of 2.5 kW. The second group was rarely entered by heaters and only when we observed a long-lasting power limit between 2 and 2.5 kW. The fourth group was not entered by heaters at all because in this case the power used by heaters would be equal to 3 kW, which exceeds the set limit.

Shading in Fig. 14–16 denotes chart regions when we observed frequent connections of other household devices to the electrical network. The region on the left corresponds to morning hours between 7 and 11. The region on the right – evening hours between 17 and 22.

Fig. 15 shows that over the morning and evening hours the chart shaded regions demonstrate long (for 60–90 minutes) and significant (up to 20–30 °C) deviations in the actual surface temperatures of heaters from the preset levels.

In other intervals over 24 hours deviations do not exceed a level of 15 °C and a time of 30 minutes.

Long lasting and significant deviations in the actual surface temperature of heaters from the preset levels over morning and evening hours led to significant deviations in the actual temperatures in some heated zones from the preset values by 4–5 °C (shaded regions in Fig. 16).

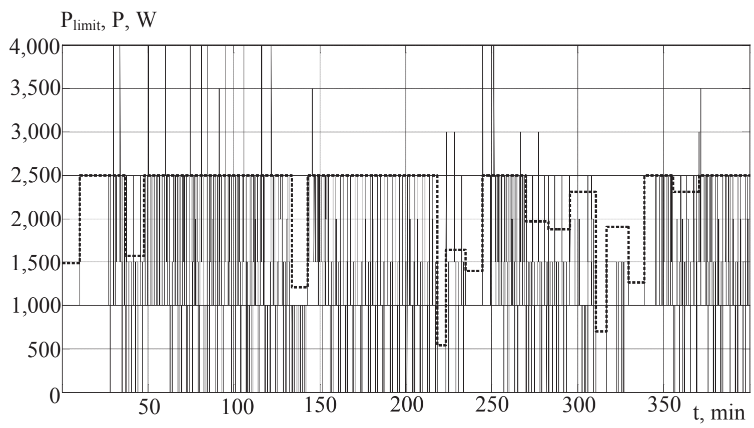

Fig. 13. Change over time in the limit of power for the electric heating of apartment (dashed line) and the total power used by heaters (solid line)

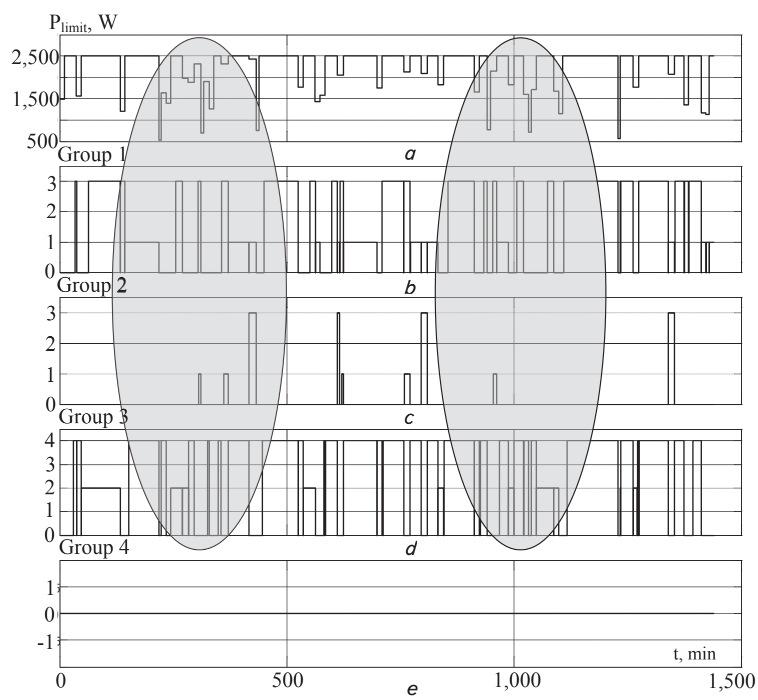

Fig. 14. Change over time:
a — the limit of power for the electric heating of apartment; *b* — number of «own» heater from the first «group»;
c — number of «own» heater from the second «group»; *d* — number of «own» heater from the third «group»;
e — number of «own» heater from the fourth «group»

Thus, the experiment showed that during morning and evening hours the established total power limit of 2.5 kW is not sufficient to ensure the set temperature modes in the heated zones. It will suffice, however, to provide for the set temperature regimes in heated zones over other hours of the day.

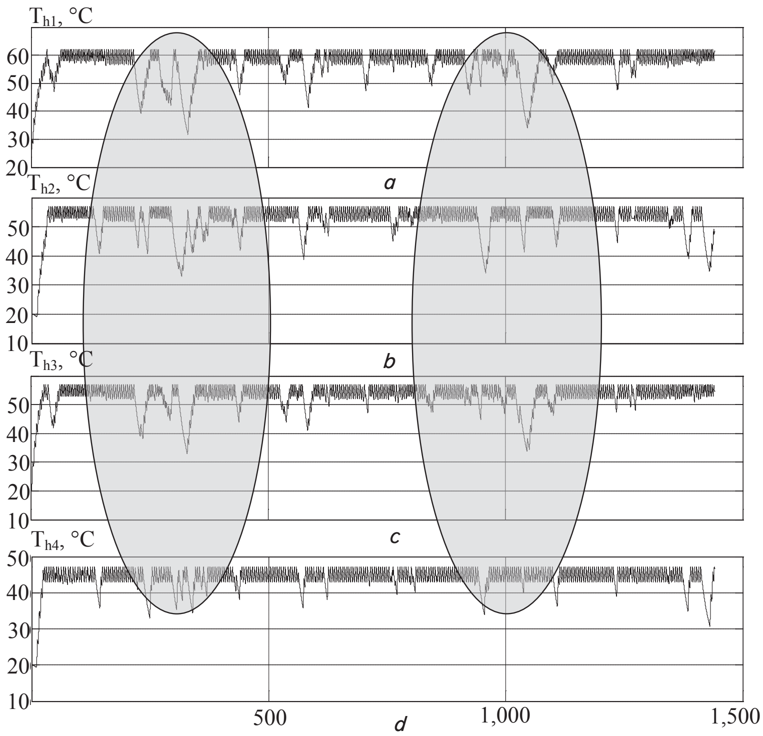

Fig. 15. Change in the temperature of surfaces over time: *a* – the first heater; *b* – the second heater; *c* – the third heater; *d* – the fourth heater

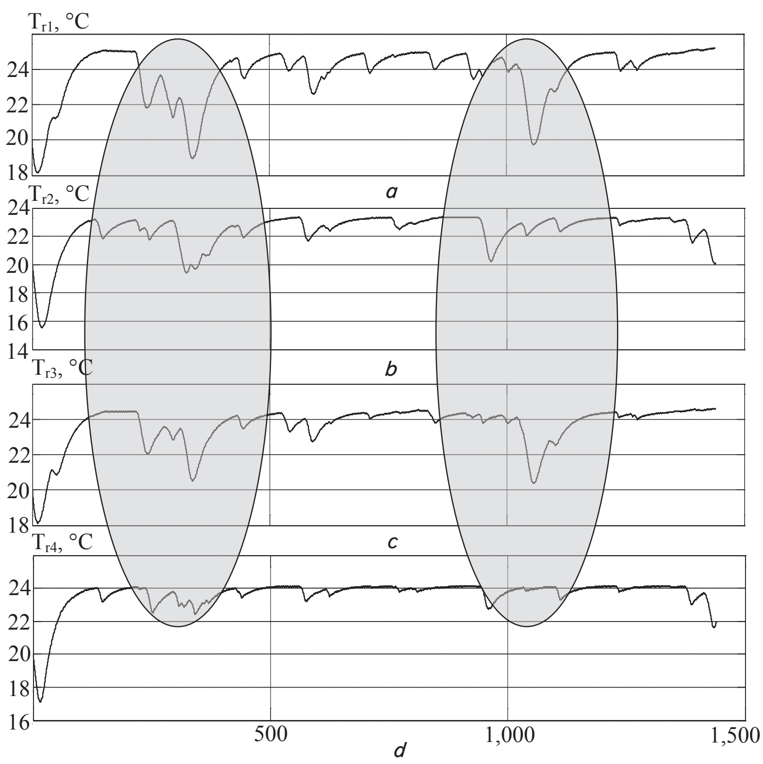

Fig. 16. Change in temperature over time: *a* – the first heated zone; *b* – the second heated zone; *c* – the third heated zone; *d* – the fourth heated zone

6. Discussion of results of studying the process of allocation of power among electrical heaters

Study of the process of allocation of power among electrical heaters using the proposed algorithm has allowed us to reveal its benefits:

– synchronization of operation of electric heaters in time takes 1–2 minutes depending on the period of operation of heaters (Fig. 7, 9). In this case, each time, under condition of change in the limit of power for electric heating, there is a new optimum combination formed from electric heaters with a high priority based on the criterion of maximizing the use of energy resource (Fig. 12). We thereby take into consideration a history of electricity consumption by a heater with the advantage given to the heaters with predicted consumption of electricity. This makes it possible for the system that manages power consumption of heaters to quickly and efficiently adapt to changing conditions of heating or the amount of electricity allocated for heating the premises. The capability of the system that manages power consumption of devices in a house to adapt, based on the proposed algorithm, to variable conditions of heating and power supply in a few minutes is the advantage over algorithms, which were suggested in other studies [6, 7, 9]. In other papers, control over power consumption by appliances is executed based on the recognition of a situation in premises and on the prediction of energy consumption using more global and integrated criteria that characterize the process of energy consumption in a house. This approach requires collecting, in real time, a large volume of previous information on the heating conditions in premises and the character of power use. That is why the adaptation is performed for such conditions of heating and power supply that change over time with a period greater by a few tens of times;

– there is a rather fast effect of change in the limit of power allocated for the electric heating of premises on temperature in the heated zones. Fig. 12–14 show that after a periodic reduction of power limit for electric heating due to the connection of other household appliances, a significant decrease in the temperature at premises, by 1 °C, occurs in 15–20 minutes. Such a rapid effect of change in the power limit on temperature in the heated zones is possible only in case when the limit corresponds to the minimum amount of electricity needed to ensure the set temperature in heated zones. The established pattern allows the user to set a temperature mode in the heated zones by assigning the limit for the power used. Thus, the user has a possibility to control the amount of electricity that is consumed for electric heating.

The shortcoming of the proposed algorithm that controls power consumption by appliances in a house is an active engagement of the user in the power management process. The user should set comfortable temperatures in heated areas by properly setting the thermostat. In addition, the user has to decide on the limit of power for heating. Given a rather large inertia of change in the temperature at premises over time, the energy management process is quite uncomfortable for the user. In the future, therefore, it is planned to create an algorithm for supporting decision-making by the user on the minimally required power limit needed to provide for the desired temperature at premises. According to this algorithm, based on the analysis of information on the dynamics of temperature at premises, it is possible to define a minimally required power limit. It would differ depending on the conditions of heating and energy consumption in a house. Each time at a significant change in the conditions of heating and energy consumption in a house, the user would be offered a new minimally required power limit to maintain the preset temperatures at premises. The user may keep the same power limit or set another value for the limit, then the algorithm would determine predicted temperatures at premises.

The proposed algorithm for the automated synchronization of power consumption by electric heaters could be used to improve existing systems that manage energy consumption in a house. As an additional feature of modern systems, it would allow private users to directly participate in the management of power consumption in their house in order to save electricity.

7. Conclusions

1. The research conducted has confirmed the possibility for the automated synchronization of operation of electric heaters in time with a different period by prolonging the time of their disconnection from the electrical network. In this case, relative deviation in the actual mean temperature of heaters surface from the preset values did not exceed 2 %. Also confirmed is the effectiveness of the application of rules of coalition consolidation or the allocation of energy resource under condition of the synchronization of operation of heaters in time. A heater that was non-prioritized, but used an excess energy resource, received 95 % of the necessary energy supply while a preset temperature was maintained at premises with this heater.

2. The study of patterns of the process of power allocation by the proposed algorithm allowed us to establish that the synchronization period of heaters in time is between 1 to 2 minutes. This makes it possible to draw a conclusion about the condition of effective application of the synchronization of operation of prioritized heaters in time in order to allocate the maximum amount of electricity to the non-prioritized heaters. The procedure of change in the optimal combination of prioritized heaters and the synchronization of their operation makes sense only when the period over which other household appliances are connected to the grid exceeds 4 minutes. We also determined the period of effect of change in the power limit on temperatures in the heated zones, which is 15–20 minutes. That is, when changing conditions of heating or power consumption, the period for the adjustment of thermal modes in heated zones due to a change in the power limit is 15–20 minutes. In this case, the deviation in actual temperature at premises from the preset values is about 1 °C. Thus, we can conclude about the possibility to control temperatures in heated zones, under condition of electrical heating at premises, by changing a power limit for heating.

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